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Abstract

Recently, changing land-use practices in the uplands of Scotland have resulted in increased re-colonisation of wet heath moorland by natural Scots pine (*Pinus sylvestris*) woodland. The simple semi-empirical water use model, HYLUC, was used to determine the change in water balance with increasing natural pine colonisation. The model worked well for 1996. However, values of soil moisture deficit simulated by HYLUC diverged significantly from measurements in 1997 when rainfall quantity and intensities were less. Measured interception by the forest canopy (interception by the undergrowth was not measured) was very different from HYLUC simulated values. By changing interception parameters to those optimised against measured canopy interception, HYLUC simulated changing soil moisture deficits better and gave more confidence in the resulting transpiration values.

The results showed that natural pine woodland interception may be similar to plantation stands although the physical structure of the natural and plantation forests are different. Though having fewer storage sites for interception in the canopy, the natural pine woodland had greater ventilation and so evaporation of intercepted rainfall was enhanced, especially during low intensity rainfall. To understand the hydrological changes that would result with changing land-use (an expansion of natural forests into the wet heath land), the modelled outputs of the wet heath and mature forest sites were compared. Evaporation, a combination of transpiration and interception, was 41% greater for the forest site than for the wet heath moorland. This may have significant consequences for the rainfall-runoff relationship and consequently for the hydrological response of the catchment as the natural woodland cover increases.

Keywords: Evaporation; interception; transpiration; water balance; Scots pine; forest

Introduction

Increasing afforestation of moorland regions in the uplands of the UK has, for a number of decades, been recognised to change the hydrological responses of these catchments. Early predictions, by Law (1956), of reduced catchment water yields with increasing afforestation, were confirmed by experimental studies (Calder and Newson, 1979; Calder, 1986, 1990, 1993). These and other studies, however, were concerned primarily with commercial conifer afforestation in the form of dense plantations; to date, literature on evaporative losses from natural pine woodlands has been unavailable.

In recent years a slow expansion of the natural Scots pine (*Pinus sylvestris*) woodland in the Cairngorm region of Scotland (Bayfield *et al.*, 1998) has become apparent. This re-colonisation of upland open moorland has been associated directly with changing land-use practices such as reduced burning and grazing (Bayfield *et al.*, 1998; French *et al.*, 1997; Bullock *et al.*, 1998). Indeed, at the site described in this paper, an increase in regeneration rate of the natural pine woodland was recorded immediately after grazing levels were reduced. Active land-use management to conserve and increase natural Scots pine woodlands has been described by French *et al.* (1997) and Bullock *et al.* (1998).

Natural pine woodlands, with an open canopy structure and pronounced undergrowth, are intrinsically different from the more homogeneous plantation stands. Consequently, it may be expected that the magnitudes of rainfall interception and transpiration from such woodlands will differ from plantation stands.

One of the objectives of ECOMONT, an EU funded project on ecological effects of land-use changes on European terrestrial mountain ecosystems, was to estimate and compare the non-winter evaporative losses from varying stages of regenerating natural pine woodland within a Scottish upland catchment. A semiempirical modelling

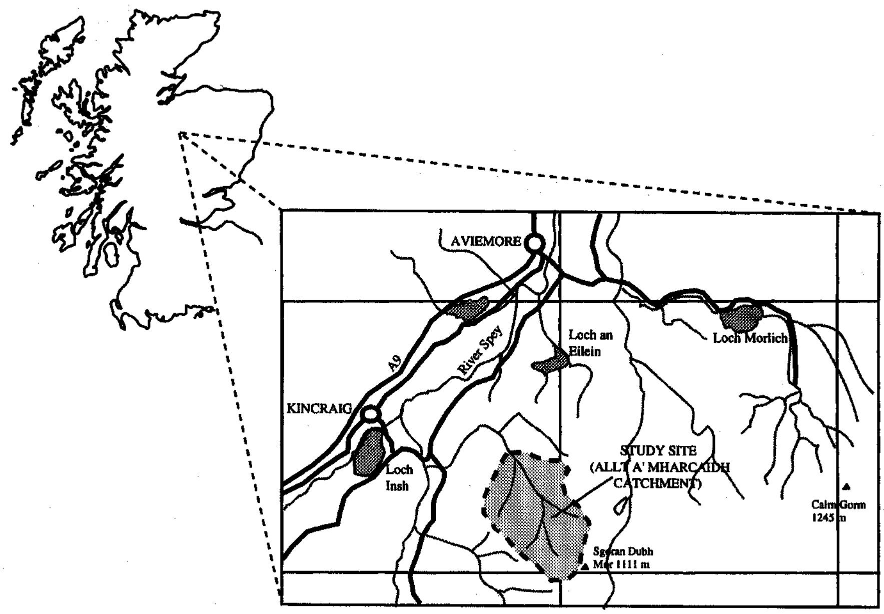

Fig. 1. *Location of the Allt a'Mharcaidh catchment in the Scottish Cairngorms.*

approach, requiring field calibration for each vegetation cover investigated (wet heath and mature forest), was adopted to describe evaporative losses in terms of transpiration and interception. As well as estimating the seasonal exchange of water vapour with the atmosphere, the approach predicts how the changing land-use will effect the seasonal moisture status of the soil and the likely implications of this for the hydrological yield of the catchment. This study is the first attempt to look at quantitative changes in hydrology resulting from natural pine woodland regeneration in upland UK.

Methods

SITE DESCRIPTION

The study site was located in the 10 km^2 Allt a'Mharcaidh catchment (57° 06.5′ N, 3° 50.5′ W) which lies on the western edge of the Cairngorm Mountains in Scotland (Fig. 1). The catchment's altitude ranges from 320 m to 1110 m and a mean annual precipitation of approximately 1000 mm (Ferrier and Harriman, 1990).

The vegetation varies from mature Scots pine (*Pinus sylvestris*) woodland on the lowest ground to moss heaths on the highest. Plantation forests exist immediately outside the catchment; within, the woodland remnants are native stands. Two study sites were instrumented. They were the wet heath site (representing the pre-pine colonisation ground cover) and the mature pine woodland site (a sample site of climax trees).

The wet heath site, situated on a podzol/peaty podzol, had a ground cover that was mainly heather (*Calluna vulgaris*), with deer grass (*Trichophorum cespitosum* (L.) Hartman) as the other major plant type, in addition to an abundance of mosses and lichens. The maximum rooting depth was 0.35 m with 95 percent of the roots within the upper 0.2 m. The soil profile was made up of an upper 0.25 m thick layer of peat below which was a 0.1 m thick layer of a mineral soil. A pronounced iron pan was present in an iron-rich horizon between 0.35 and 0.6 m, below which were glacial boulders and sand. It was noticeable that the roots did not penetrate the iron pan.

The mature forest site, again on a peaty podzol, was of established *Pinus sylvestris* with an average age of 170 years. The average tree height was 15 m and the site had a tree density of 275 trees per hectare. The ground cover below the canopy was of bilberry (*Vaccinium myrtillus* L.), cowberry (*V. vitis idaea* L.) and mosses. The maximum rooting depth was 0.7 m with 95 percent of the roots within the upper 0.48 m. The soil profile was made up of an upper 0.4 m thick layer of peat below which was a 0.4 m thick layer of a mineral soil. A pronounced iron pan was again present in an iron-rich horizon of between 0.8 and 1.3 m, below which were glacial boulders and sand. Again, no roots were evident below the iron pan.

A detailed description of the vegetation and soils of the catchment is presented by Bayfield and Nolan (1998).

THE MODEL

The HYdrological Land-Use Change (HYLUC) model has been developed from process studies to describe the evaporative losses from conifer plantations in the uplands of the UK (Calder, 1977, 1986, 1990; Hall and Harding, 1993; Price *et al.*, 1996). Conceptually the model can be split into three component parts describing Soil Moisture Deficit

(*SMD*); daily Transpiration losses (*T*); and daily Interception losses (*I*). The model works on a time step of one day and as input data requires only daily rainfall (*P*) and Penman potential evaporation (E_T) (Penman, 1948). The three component parts are described by the following equations in which the *i* and *i*-1 subscripts denote the variable values for the i^{th} and $(i-1)^{th}$ daily time steps:

$$SMD_i = SMD_{i-1} + T_i + I_i - P_i \qquad (1)$$

$$I_i = \gamma.(1 - e^{-\delta P_i}) \qquad (2)$$

$$T_i = \beta.E_T.(1-\omega) \qquad \text{for } SMD_{i-1} \leq A_w/2 \qquad (3a)$$

$$T_i = \beta.E_T.\left(1 - \frac{SMD_{i-1} - A_w/2}{A_w/2}\right)(1-\omega) \qquad \text{for } SMD_{i-1} > A_w/2 \qquad (3b)$$

where γ (mm) and δ (mm^{-1}) are interception parameters. The parameter γ is the maximum predicted interception loss in 1 day. β is a transpiration factor that scales the dry period transpiration rate of the trees to the Penman potential. ω is the fraction of the day that the vegetal canopy is wet. A_w (mm) is the available water to the vegetal root system (Price *et al.*, 1996). It is assumed that, if field capacity is exceeded, the moisture content of the soil will, in the absence of precipitation, return to field capacity after one day. The model was not applied in the winter months to avoid changes in soil moisture content caused by snow cover and snow melt that would differ between the experimental sites.

Since the development of the model for coniferous plantations in the UK uplands it has been successful in describing the evaporative losses from other land-uses such as: heather rich moorland in the UK (Hall, 1987; Hall and Harding, 1993); Scottish upland grassland (Wright and Harding, 1993) and *Eucalyptus* and native woodland in India (Harding *et al.*, 1992). In a simplified form, the model has described the impact of land-use change in southern Africa (Calder *et al.*, 1995) and East Africa (Roberts and Harding, 1995). In each case, the HYLUC parameters were obtained from detailed process studies.

EXPERIMENTAL DETERMINATION OF MODEL PARAMETERS IN THE ALLT A'MHARCAIDH

A measure of transpiration and interception rates associated with each plant community is required to establish the HYLUC parameter values. Therefore, experimental techniques that monitor the integrated evaporative losses from the vegetation communities are preferable to techniques that measure only component parts, such as individual trees, within the plant community. In this study, techniques measuring atmospheric fluxes above the canopy, such as eddy correlation or Bowen ratio, were rejected in favour of soil moisture techniques due to the site having an uneven topography coupled with a relatively high average wind speed.

For the methodology to succeed several criteria needed to be met:

- Measurable soil moisture deficits develop over a substantial length of time during the non-winter season.
- Soil moisture sampling encompasses more than the full depth of the root systems.
- Roots cannot access water from the water table.
- Sufficient volumes of soil are monitored to reduce the uncertainty associated with the heterogeneous nature of both the soil and vegetation environments.
- Saturated flow, either to or from the soil monitored, does not occur during periods of soil moisture deficit.
- Unsaturated drainage is negligible.

If these criteria are met, then transpiration can be estimated directly from the depletion rate of soil moisture during dry periods (Calder, 1990; Harding *et al.*, 1992) and interception rates can then be inferred from Eqn. 1.

SOIL MOISTURE MEASUREMENT

Soil moisture measurements were made using a neutron probe in accordance with procedures described by Bell (1976). Aluminium access tubes were installed beneath each vegetation type beyond the depth of the rooting zone by manually augering out soil ahead of a steel guide tube to minimise disruption to the soil structure. However, where the soil was too hard, due to the presence of weathered rock fragments, a combination of rotary and percussion drills was used in conjunction with the guide tube. Seven tubes were installed randomly in the mature forest to give a profile depth of 1.45 m, whilst four tubes (a profile depth of 0.95 m) were installed along a down slope transect at the wet heath site. In 1996 and 1997 neutron probe measurements were made at both sites at approximately weekly intervals during the spring, summer and autumn, and at a reduced frequency during the winter. In 1998 readings were taken only at the mature forest site. Tubes were read at constant 10 cm depth intervals. A borehole deeper than 6 m was drilled at the mature forest site to investigate the likelihood of tree roots abstracting water from the water table.

CLIMATE MONITORING

Ground level storage rainguages (Rodda, 1967), read weekly, were used to measure rainfall at each experimental site. These weekly data were time-distributed into daily values using daily data from a tipping bucket rainguage. An Automatic Weather Station (AWS), comprising solarimeter, net radiometer (1 m above ground), wet and dry bulb thermometers, anemometer (2 m above ground), wind direction and a tipping bucket raingauge, supplied the data necessary for the calculation of E_T. The AWS was situated on open heathland and located centrally within the catchment.

ANALYSIS METHODOLOGY

The β transpiration parameter values in the HYLUC model were obtained from neutron probe data by summing dry period changes in soil moisture deficit and comparing these to the equivalent E_T totals. ω was obtained by establishing a relationship between the daily rainfall duration and rainfall amount. The interception parameter γ was obtained by optimising Eqn. 1 such that the soil moisture deficit predicted matched the observed data. Modelled soil moisture deficit curves, calculated with varying values for γ, were positioned to minimise the objective function:

$$\sum_{i=1}^{n}(SMD_i - SMD_{np,i})^2 \qquad (4)$$

where SMD_i represents the modelled soil moisture deficit on the i^{th} day, and $SMD_{np,i}$ is the measured value derived from the neutron probe data. δ values were initially treated as constants during the optimisation, and were taken to be 0.099 for the mature forest site, and 0.36 for the wet heath (Calder, 1990). Available water (A_w) constants were given values of 150 mm for the wet heath and 200 mm for the mature forest site (Price *et al.*, 1996).

Field capacity values for each site were obtained by a similar optimisation procedure, (Calder *et al.*, 1983). The calibrated model parameters were used in the model and trial field capacities were adjusted until the best fits were obtained between the observed and predicted values for the full data set including the periods when field capacity was exceeded.

MODEL TESTING

To assess the accuracy of the calibrated model, the amount of interception from the forest canopy was measured at the mature forest site, in the 1998 field season. A 400 m^2 grid (100 m × 4 m) was marked out on the forest floor where 39 throughfall collectors were randomly placed. Each throughfall collector comprised of a 0.18 m (i.d.) diameter funnel fitted through a rubber stopper to a plastic collecting bottle. The whole apparatus was attached to a wooden stake which could be inserted into the ground surface. Approximately weekly, the amount of throughfall collected was measured, the bottles emptied, and the collectors replaced in their new randomly generated locations within the grid. To account for evaporation during the week, 2 extra collectors, situated outside and at opposite ends of the grid under a rain shelter, were filled with a known quantity of water when the experiment was started. The rain shelter was supported about 0.3 m above the top of the funnel to prevent rainfall entry but also to allow, as far as possible, the free movement of air over the funnel. When measuring throughfall, the amount of water in the sheltered collectors was also measured and evaporation calculated. Measured canopy interception was compared with predicted interception. Interception by the forest undergrowth was not measured.

Stemflow at the mature forest site was measured for three trees in September, October and November in 1997. 12 mm rope, wound around the tree at an angle, covered by a clear plastic sleeve, formed the base of the stemflow collector. More rope was wound around the sleeve to hold it in place. The 12 mm rope, bridging the gap between the plastic sleeve and the tree stem, was covered with a plastic resin as a base, which in turn was sealed with silica sealant. The three stemflow collectors were leak tested. Water flowing down the stem was channelled to a tipping bucket gauge that recorded data hourly.

Results

SOIL MOISTURE

During the summer and autumn of 1996, soil moisture data (not shown) indicated that the neutron probe tubes were sufficiently deep to penetrate to depths where the soil moisture had changed little; this suggested that the whole rooting zone at each site had been monitored. Soil pits at each site provided visual confirmation that the iron pan prevented deep root penetration and, consequently, water uptake from depth in the profile. A comparison of vertical root distribution with water removal from the soil profile during an 18 day dry period in 1996 showed good agreement between the location of roots and water depletion at the mature forest site, and reasonable agreement at the wet heath site.

During the study period a free water table was observed at the mature forest site only at a depth of 6 m, however, the roots and the water table were never less than 5 m apart. Given the sandy nature of the underlying glacial deposits and the slope angles, it is unlikely that the water table effected the experimental results.

At the mature forest site during 1998, the profile water content exceeded field capacity for almost all the season (Fig. 2); without a developed soil moisture deficit the calibration of the model was not possible. Only in the 1996 and 1997 field seasons did significant soil moisture deficits develop at both sites (Figs. 3a and 3b). However, observed values showed that a much smaller deficit developed at the wet heath site (Fig. 3b), whereas the magnitude of the deficit at the mature forest site (Figs. 3a) was considerably larger. Consequently, the wet heath soil reached field capacity more than 20 days earlier than the forest site.

For the mature forest site, analysis of data from individual neutron probe tubes showed counts approaching, and in some cases exceeding, the calibrated water count for the

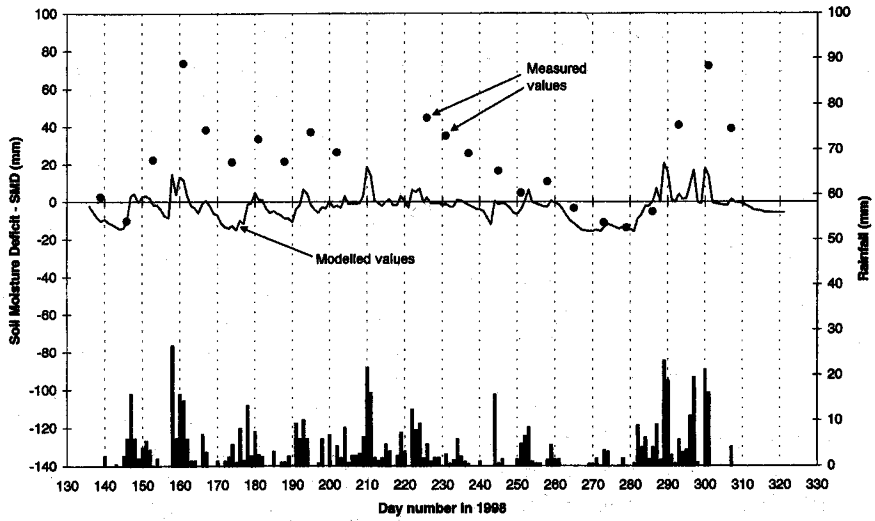

Fig. 2. *Time-series measured and modelled values of soil moisture deficit, at the mature forest site, in 1998.*

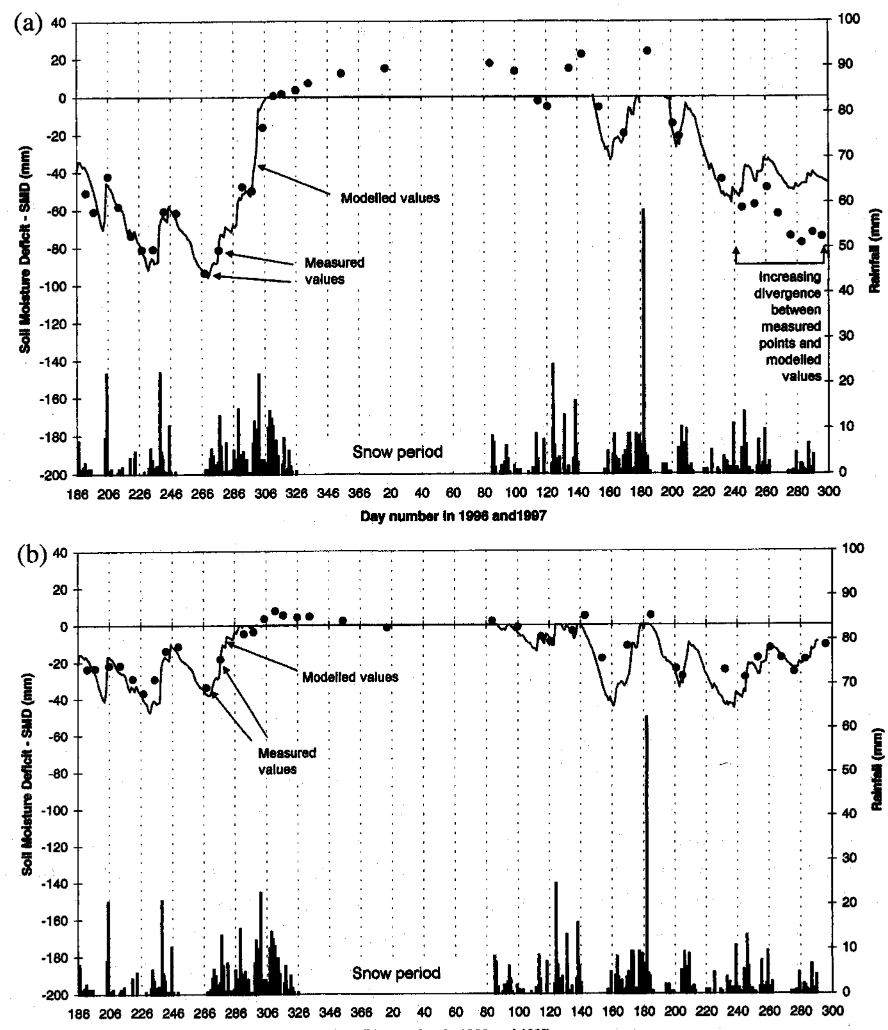

Fig. 3. *(a) Time-series measured and modelled values of soil moisture deficit, at the mature forest site, in 1996 (model calibration) and 1997 (model validation). (b) Time-series measured and modelled values of soil moisture deficit, at the wet heath site, in 1996 (model calibration) and 1997 (model validation).*

Table 1. Data used in the calculation of the β transpiration parameter.

Site	*Number of days*†	*Penman (E_T) (mm)*	*ΔSMD (mm)*	*β*	*β Std dev. (±)*
Wet heath	18	43.2	23.9	0.55	0.18
Mature forest	18	43.2	32.0	0.74	0.12

† Total duration of the dry periods used in the calculation of β.

layer above the iron pan. These results indicate the influence of a high soil organic carbon content and the likely development of a saturated perched water layer. The development of a sustained perched water table appeared to be dependent on the intensity and duration of rainfall; on Day 182 in 1997 a 58 mm storm produced an ephemeral perched water table which was sustained for only a short period. In 1998, however, the nature of the rainfall appeared to sustain a perched water table for much of the season. This will have had implications for lateral water flows and deep drainage that will be discussed later.

MODEL PARAMETERISATION AND DEVELOPMENT

By plotting the duration of rain events against the daily rainfall in the catchment, a curve was fitted to the data ($R^2 = 0.86$), from which an expression for ω was formulated:

$$\omega = \frac{1.66P^{0.67}}{24} \tag{5}$$

where ω is the fraction of the day that the vegetal canopy is wet, and P is the daily rainfall (mm).

The magnitudes of measured soil moisture deficits proved small enough not to require the transpiration constraining function (Eqn. 3b) to be used in the model's calculation of soil moisture deficit.

The details regarding the calculation of the β transpiration parameters are given in Table 1. Values at both sites were calculated using mean site changes in soil moisture deficit (ΔSMD) from dry periods occurring in September 1996. The uncertainty in the β values was calculated from the standard deviation of the individual tube values.

The optimised γ interception parameters are given in Table 2. Since the interception parameter γ was optimised against SMD (Eqn. 1), where both SMD and P were measured variables, the degree of uncertainty in γ will be dependent on β. Therefore, the uncertainty in the values was calculated by running the optimisation procedure with β values plus or minus their standard deviations.

Table 2. The optimised γ interception parameters given constant δ values.

Site	*δ (constant)*	*γ (optimised)*	*γ uncertainty (±)*
Wet heath	0.36	0.9	2.0
Mature forest	0.099	2.6	1.9

The model was initially calibrated against measured soil moisture deficits, for the 1996 season, using δ constants derived from studies by Calder (1986,1990) for plantation forests and heather. The performance of the model was tested against measured soil moisture deficits in 1997. The results of the 1996 calibration and 1997 performance testing are shown for each site in Figs. 3a and 3b (mature forest and wet heath respectively).

For the early part of 1997 (Days 85 to 200), soil moisture deficits fluctuated around field capacity and, as the model could only be applied where a significant deficit had developed, the useable data were restricted to the period between Days 200 to 300. After this period, snowfall prevented application of the model. For these periods in 1997 the model matched the observations until approximately Day 240 for the mature forest site, from which time the modelled soil moisture deficit began to deviate significantly from the measurements. This period of increased divergence between modelled and measured data appeared to coincide with periods of less intense rainfall; the daily average annual rainfall intensities at the mature forest site (based on rainfall days only) were 4.35, 4.02 and 4.93 mm day^{-1} for 1996, 1997 and 1998 respectively. In 1997 however, from Days 200–300, the rainfall intensity fell to 2.99 mm day^{-1}. Hourly data from the weather station showed the non-winter rainfall intensity in 1996, for rainfall days only between Days 186 to 326, to be 0.12 mm hr^{-1}. For the model run in 1997 (Days 200 to 300), the rainfall intensity was a third less at 0.08 mm hr^{-1}. The greatest rainfall intensity for the non-winter season was in 1998, averaged at 0.15 mm hr^{-1} based on rainfall days only. In 1997, the model simulated observations for the wet heath site (Fig. 3b) better than for the forest site.

Figure 4 shows rainfall against the measured canopy interception and the modelled total interception, using the parameters established by Calder (1986, 1990), which were optimised against measured soil moisture deficit. Because of the significant difference between modelled and measured interception, the interception parameters δ (mm^{-1}) and γ

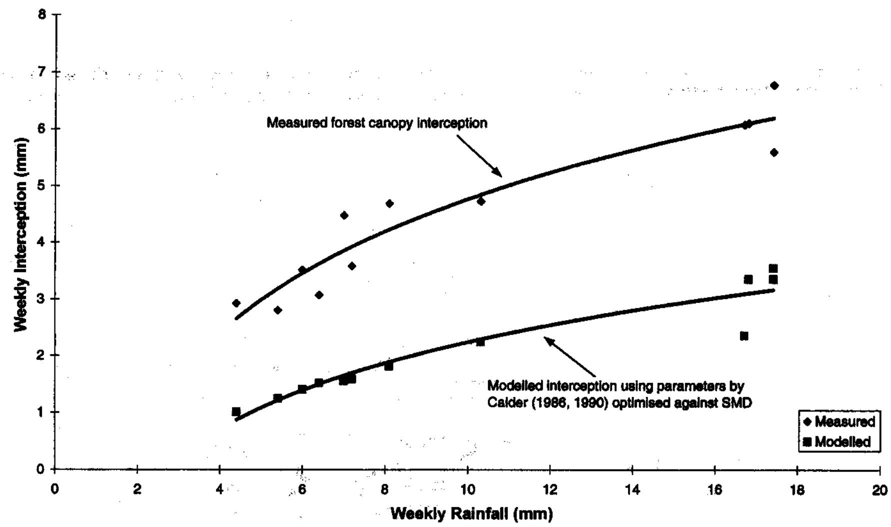

Fig. 4. *Rainfall against measured forest canopy interception and modelled total interception, at the mature forest site, in 1998.*

(mm) were both optimised against the measured interception; the new parameters are shown in Table 3. The uncertainty values were calculated by rearranging Eqn. 2 to identify γ and δ as the objective functions (Eqns. 6 and 7 respectively). When calculating γ, δ was constant at 0.064; and when calculating δ, γ was constant at 7.5. The uncertainty was calculated as the positive and negative standard deviations in γ and δ for the measured values of interception.

$$\gamma = \frac{I}{(1 - e^{-\delta P})} \tag{6}$$

$$\delta = -\left(\frac{\ln\left(-\frac{I}{\gamma} + 1\right)}{P}\right) \tag{7}$$

MODEL RESULTS

Replacing the interception parameters set up for the mature forest site at the start of the exercise (Table 2) with the parameters optimised against measured canopy interception (Table 3), improved the prediction of the modelled soil moisture deficit (Fig. 5), especially for the latter part of 1997 (Day 200 to 300). However, when optimised to soil moisture deficits for 1996, the fit was not as close as with the original interception parameters. Specifically, in 1996, the model underestimated the soil moisture deficit (predicted a wetter soil profile than was measured) during the drying phase. This is discussed later.

Values for precipitation, P, interception, I, transpiration, T, total evaporation (the sum of interception and transpiration), E, and Penman potential evaporation, E_t, were either measured or estimated from the model results for 1996, 1997 and, at the mature forest site only, in 1998. For the mature forest site, the interception parameters used were those optimised against measured interception (Table 3). Hydrological ratios produced comparable information about processes occurring between different land-uses for the non-winter periods. The mature forest data (Table 4) are compared with data from the wet heath (Table 5).

Stemflow measurements showed 0.3% of rainfall on average was transported via this mechanism to the soil. During the most intense rainstorm, the value only increased to 0.6%. These results agree well with those presented by Gash and Stewart (1977) for a plantation woodland.

Discussion

SOIL MOISTURE

Although changes in the moisture status below the rooting zone during dry periods were negligible, indicating vertical drainage may not be significant when the moisture status of the soil was below field capacity, the true significance of sustained matrix drainage was unquantified. The model also made no consideration of deep drainage by preferential water flow by-passing the soil matrix either through

Table 3. Optimised γ and δ interception parameters based on measured canopy interception data.

Site	*δ (optimised)*	*δ uncertainty (±)*	*γ (optimised)*	*γ uncertainty (±)*
Mature forest	0.064	0.018	7.5	1.26

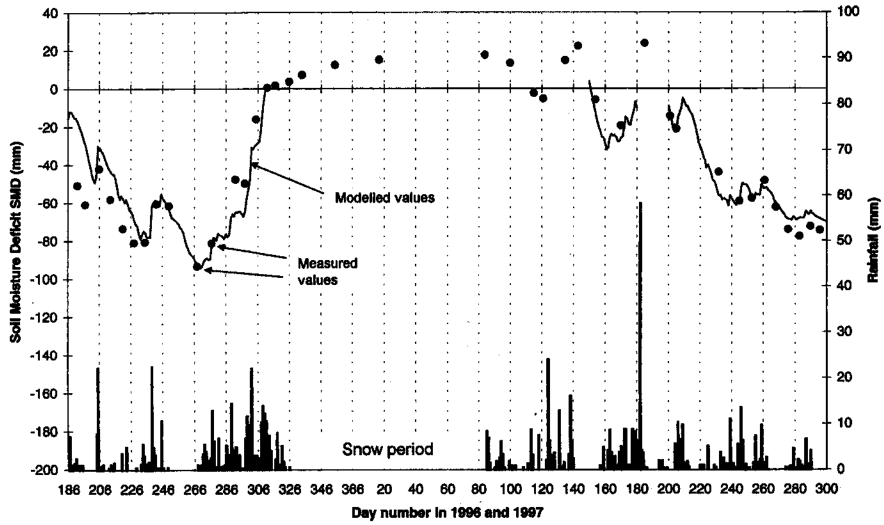

Fig. 5. *Time-series measured and modelled values of soil moisture deficit, at the mature forest site, in 1996 and 1997, using re-calibrated interception parameters.*

macropores or through wetter regions of increased hydraulic conductivity; water was likely to collect in areas where the slope flattens, so increasing the likelihood of vertical drainage. If soil water monitoring did not encapsulate these sites, and indeed if the preferential recharge was rapid during and after a rainstorm, these events were likely to remain unobserved by the limited spatial and temporal monitoring regime.

Evidence of a saturated perched water layer above the iron pan at the mature forest site in 1998 suggested interflow may have been an important process under certain conditions. This may be more significant for the wet heath, which developed smaller soil moisture deficits. The relationship between interflow and vertical by-pass flow, especially immediately after rainstorms, may further complicate the understanding of processes, and consequently of model predictions, at the site. Interflow is thought likely to occur above field capacity, though this would not detrimentally effect the calculation of the HYLUC parameters since the model is designed to be applied for periods of soil moisture deficit.

MODEL PARAMETERISATION AND DEVELOPMENT

Initial optimisation procedures provided a good model fit and supported the applicability of HYLUC in this environment. However, when the optimised model was applied to 1997 mature forest data, the model fit was disappointing; this indicated that the model was in error or that some of the underlying processes were poorly understood.

In 1997, for the mature forest, the model predicted a soil moisture deficit smaller (i.e. the soil was wetter) than was measured by a maximum of about 30 –40 mm within the profile for the duration of the model run. The processes that may have led to this are: i) increased transpiration, ii) increased interception, iii) losses through drainage and interflow or iv) a combination of these processes. There is some evidence to show that the divergence between measured and modelled soil moisture deficit may be associated with reduced rainfall intensity. The significance of these processes is discussed below.

In considering transpiration, the wet heath β value of 0.55 compares well with previous similar studies on heather rich moorland: 0.58–0.67 by Calder *et al.* (1982); 0.47 again by Calder (1990); 0.25–0.5 by Wallace *et al.* (1982). The mature forest β value of 0.74 is sufficiently different from the equivalent conifer plantation value of 0.9, presented by Calder (1986), to suggest differing rates of transpiration between the two types of land cover.

The initially optimised γ interception parameters (Table 2) show, as expected, marked differences; though the magnitudes of the uncertainties are large, and as such can represent only crude estimations of interception and a potential source of errors. The wet heath γ value of 0.9 is smaller than the value of 2.65 suggested by Calder *et al.* (1986) for heather moorland. This is perhaps to be expected since the wet heath site consists of a relatively sparse and low (~16 cm) canopy of heather, deer grass, lichen and moss, whilst the canopy described by Calder was approximately twice the depth and more dominated by heather.

The initial mature forest interception parameter, γ, is much lower than values estimated for UK conifer plantations. Calder (1986) summarises the interception values for upland plantations in both Scotland and Wales, giving mean values of γ and δ as 6.99 and 0.099 respectively; and values established specifically at Aviemore (only 6 km from the Allt a'Mharcaidh) are 7.1 and 0.099. The canopy interception study conducted in 1998 tested the validity of the initial interception parameters and indicated the potential errors involved in optimising against soil moisture deficit. Optimising both γ and δ against measured interception gave values of 7.5 and 0.064 respectively; the former value agrees closely with Calder (1986).

Substituting these interception parameters into the model improved considerably the fit of the modelled results to the measurements for the mature forest site, especially over Day 200 to 300 in 1997 (Fig. 5). However, the goodness of fit deteriorated in the latter stages (day 275 to day 300) of the run in 1997, when the model predicted a wetter soil profile than was measured. This was more evident in 1996, with the model predicting a wetter soil profile during the drying phase. The most obvious difference between 1996 and 1997 was in rainfall intensity, with more intense rainfall potentially exacerbating the hydrological processes of water loss (such as unobserved vertical drainage and interflow) from the measured profile. A more likely reason, however, is the omission of undergrowth interception from the model, which will probably have a greater impact on the soil moisture deficit during intense rainfall. During low intensity rainfall there would be greater forest canopy interception and the relative impact of undergrowth interception would be less. Gash and Stewart (1997) found bracken interception to account for 4.5% of rainfall in a managed pine woodland. Clearly more work is needed to understand the relationship between rainfall intensity and interception.

Stemflow accounted for less than 1% of the water balance at the mature forest site. Consequently, the transfer of water to the soil by this mechanism, which can by-pass undergrowth interception, is clearly not significant.

MODEL RESULTS

In comparing model predictions for land-use change from wet heath to a natural mature forest we need to consider the results in Tables 4 and 5. Since the wet heath and mature forest sites were in close proximity, the climatic conditions were very similar, and so differences between the sites will represent differences in plant water use. Of the rainfall in the non-winter months, an average (over 3 years) of 61% was evaporated (a combination of transpiration and interception) from the wet heath whereas for the mature forest the figure averages to 102%. The mean interception at the wet heath site (13%) was more than doubled by the established mature forest (37%) whilst transpiration of rainfall increased from 48% at the wet heath site to 65% for the mature forest. Establishment of a mature forest would therefore increase the water use by about 41% over the wet heath; however, this value varies considerably from year to year depending on climatic conditions such as rainfall intensity.

Table 4. Non-winter hydrological ratios for the mature forest site after optimisation against measured interception.

Mature forest	*1996 Days 186–326*	*1997 Days 200–300*	*1998 Days 140–321*	*Mean*
Rainfall (mm)	348	153	582	361
I/P	0.36	0.40	0.35	0.37
T/P	0.55	1.03	0.37	0.65
E/P	0.91	1.43	0.72	1.02
T/E_t	0.70	0.70	0.67	0.69
E/E_t	1.17	0.97	1.32	1.15

Table 5. Non-winter hydrological ratios for the wet heath site.

Wet heath	*1996 Days 186–326*	*1997 Days 200–300*	*1998 Days 140–321*	*Mean*
Rainfall (mm)	342	147	580	356
I/P	0.12	0.16	0.11	0.13
T/P	0.41	0.76	0.27	0.48
E/P	0.53	0.92	0.38	0.61
T/E_t	0.52	0.52	0.50	0.51
E/E_t	0.67	0.63	0.70	0.67

Interception between plantation forests and mature natural woodland was shown to be similar; however, due to the differences in structural architecture between the two forest types, it is hypothesised that the contribution of different mechanisms of interception may differ significantly. Plantations, where the canopy cover and tree density is usually greater, may intercept and hold greater volumes of rainfall; however, with reduced air movement within the canopy, the evaporation of the intercepted water is restrained. The natural pine woodland, with a more open canopy and therefore fewer sites for interception of water, but with greater ventilation and reduced aerodynamic resistance enhancing the evaporation of intercepted water, will intercept and evaporate water in similar quantities to plantation stands. Calder (1990) observed similar results in upland Wales where, in a plantation woodland, interception ratios remained unchanged before and after thinning of the trees. Indeed, comparing I/P ratios, the values predicted from the corrected interception parameters, range from 0.35 to 0.4 (35 –40%) which is in good agreement with published values for plantation stands (Calder, 1990; Tallaksen *et al.*, 1996). It is noteworthy that the highest seasonal interception (40%) was during a period of low intensity rainfall (0.08 mm h^{-1}) in 1997, with the lowest interception (35%) during the highest seasonal rainfall intensity (0.15 mm h^{-1}) in 1998. The lower rainfall intensity most likely provides greater opportunity for interception sites to be emptied in the natural mature forests with greater ventilation compared with plantation stands. Therefore, during extended periods of low intensity rainfall, the natural pine forest may be far more effective at intercepting rainfall than the plantation forests.

Different land-uses affect the environment in more ways than just the transfer of moisture to the atmosphere. The moisture status of the soil environment is clearly affected by the type of vegetation system present. The influence of forest rooting systems can vary the conditions to greater depths, and the forest soils may be subjected to larger soil moisture deficits than the wet heath moorland site. As a result the wet heath soils may wet up and reach field capacity earlier, enabling the onset of saturated flow processes to occur before they do in the woodland. The hydrological changes resulting from changing land-use and biophysical interactions are likely to affect, in the long term, the soil fauna, soil flora and soil chemistry. More immediately, these changing processes may have significant repercussions for catchment hydrology and rainfall runoff relationships.

Conclusions

Evaporation from natural pine woodland colonisation in upland Scotland was modelled using HYLUC, a simple one-dimensional model developed for studies in plantation forests. The model, calibrated on site against measured soil moisture deficits, worked well in 1996 but with only limited success during periods of low intensity rainfall in 1997. Interception measurements showed how the interception parameters were inappropriate; once optimised against measured interception, even though undergrowth interception was not measured, the model provided better results. Stemflow was shown to be insignificant. The improved interception results, compared with results from plantation forests, showed that similar amounts of rainfall may be intercepted although the physical structure between the natural and plantation forests may be very different. Though fewer storage sites are available for interception in the canopy, the natural woodland has greater ventilation, and therefore the evaporation of the intercepted rainfall may be enhanced.

To understand the change in hydrological processes that would result with changing land-use (an expansion of natural pine woodland into the wet heath land), the modelled output between the wet heath site and mature forest site were compared. Evaporation, a combination of transpiration and interception, was 41% greater for the forest site than the wet heath. This is likely to have significant consequences for the rainfall–runoff relationship and consequently for the hydrological response of the catchment as forest cover increases.

Although not considered in this paper, account needs to be made of potentially large winter losses from snow intercepted by the forest canopy (Lundberg *et al.*, 1998). This process needs to be considered for physically based water resource modelling over both the winter and non-winter periods.

The simple one-dimensional model used may be susceptible to the extreme heterogeneity of these mountain regions both in terms of climatic variability and complex soil water processes. The study emphasised the potential errors that may arise from the use of simple models with a limited knowledge of processes. For these models to provide a meaningful understanding of the hydrology, the model parameters need to be site specific, so requiring some degree of experimental work to investigate the processes. This study has shown that, despite the limitations of such models, their semi-empirical application can be successful in providing a greater understanding of processes in a very complex environment.

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